BACKGROUND PAPER #4: SITE PLANNING

INTRODUCTION

This paper examines site planning issues in coastal areas susceptible to tsunami events. It focuses on how to assess a site for hazards; establish a design review approach for new coastal investment; and develop mitigation strategies for various types of development.

The physical configuration of structures and uses on a site—including the siting of structures, location of open space areas, interaction of uses and landforms, design of landscaping, and erection of barriers—can reduce potential loss of life and property damage when development is to be sited within a tsunami hazard area. Within the broader framework of a comprehensive plan, site planning determines the location, configuration, and density of development on particular sites and is, therefore, an important tool in reducing tsunami risk.

Companion Background Paper #3 focuses on avoiding tsunami hazard areas through land use planning, while Background Paper #5 addresses reducing tsunami damage through building design.

KEY CONCEPTS AND FINDINGS

There are three key concepts that organize this background paper.

Concept 1: Create a Project Review Process that is Cooperative, Comprehensive, and Integrated

While Background Paper #2 summarizes the federal, state, and local regulatory context for coastal areas, Background Paper #4 focuses on how local planning officials or project sponsors can work with others to develop tsunami mitigation strategies. This includes:

- Agreeing on the level and nature of risk of the site;
- Exploring mitigation alternatives; and
- Integrating mitigation strategies in the development review process.

Concept 2: Understand Local Site Conditions

Background Paper #1 discusses the global and regional context and sources for understanding tsunami hazards. However, local planning officials and project sponsors have to be able to develop mitigation strategies reflecting the character of the site and immediate context. This includes understanding how tsunamis impact various types of:

- Site geography and configuration;
- Land uses and building types; and
- Development patterns.

Concept 3: Choose a Mitigation Strategy for the Site

This site planning paper provides a general set of methods and techniques that can be applied to projects. It applies four overall techniques to create site-specific mitigation strategies. These methods involve ways to:

- Avoid inundation areas;
- Slow water currents;
- Steer water forces; and
- Block water forces.

WORKING WITH PROJECT SPONSORS

Local planning officials and project sponsors must work with others to develop tsunami mitigation strategies. This requires that project participants:

- Agree on the level and nature of risk on the site;
- Explore mitigation alternatives; and
- Maintain mitigation strategies in the development review process.

This section of Background Paper #4 focuses on understanding the regulatory context, basic steps in the site design process, and how to include tsunami mitigation in the planning process.

Understanding the Context: Federal, State and Local Regulations

Every project has a set of federal, state, regional, and local policies and regulations that have to be satisfied. Understanding the regulatory context is critical in the site planning process.

State and Federal Policy and Regulatory Context

Every coastal community in the five Pacific states has a land use planning and regulation process that responds to state mandates or guidelines. Most states have statewide planning guidelines, require local plans to be consistent with state policies, and require hazard mitigation in local comprehensive plans and environmental review (see Background Papers #2 and #3). Federal Flood Insurance mandates projects be located above the 100-year flood or inundation areas.

Many states require public access or use of waterfront areas as well. These regulations limit the location, uses, and character of development and become part of the equation for new coastal investment.

Local Regulations

At the top of the local land use planning/regulatory process hierarchy is the community's comprehensive plan. The comprehensive plan is implemented day-to-day through "current planning" project review and permitting. Local governments typically require formal approvals for land divisions, the establishment of certain new uses ("conditional uses"), and the physical layout of new development. At the site planning level in the planning/regulatory hierarchy, the focus typically is on a single parcel or collection of parcels of land two to 200 acres in size, under the control of a single owner. This scale of planning provides limited opportunities for avoiding the tsunami hazard entirely, but can still provide a broad range of opportunities to design a project to minimize tsunami damage.

Site Planning and Review Process

The most effective site planning in coastal areas includes a project review process that reflects the area's vulnerability and exposure to tsunami hazards, considers the larger policy and regulatory context, and is a part of a larger mitigation strategy. An interactive and informed site planning and review process can save time for project sponsors and provide better mitigation solutions.

Communities interact with project proponents at various levels in the preparation and review of site plans. The level of review relates to the scale and context of a project. Some projects require site and concept review, while others require a review of fully developed designs. Community-level project review can take place parallel to the design process in an interactive fashion. Alternatively, project site review can be more reactive based on predetermined criteria or plans.

Some communities have adopted comprehensive development policies for waterfront areas to ensure that site planning is part of a review process that implements a larger mitigation plan, economic objectives, and community design concepts. Without this broader framework, community-wide mitigation objectives can be overlooked in a site plan review process that involves different disciplines and multiple departments and decision-making bodies.

Site Analysis: Setting the Mitigation Framework

The site analysis phase can be used to establish site plan parameters for tsunami hazard mitigation. Many communities have already mapped hazard areas (although these maps are not always reliable at the scale of a single site). Within these areas, communities may also have area plans that have included site analysis. The analysis typically includes geographic conditions, landscape, critical infrastructure (see Background Paper #6), area access and egress (see Background Paper #7), and existing and future development patterns. Experts should be consulted to accurately define the hazard area. Other considerations include economic feasibility and community design objectives.

UNDERSTANDING LOCAL SITE CONDITIONS

Local planning officials and project sponsors must develop mitigation strategies reflecting the character of the site and immediate context. This includes understanding how tsunamis impact various types of site geography, land uses and building types, and development patterns. The depth of tsunami inundation, speed of currents, presence of breaking wave or bore conditions, debris load, and warning time can vary greatly from site to site.

Understanding the Context: Regional Geography and Multiple-Hazards

At the local level, the geographic context has an important bearing on the amount of risk exposure in an area. In all five Pacific coastal states, hazards maps are available, being updated, or underway that define elevations and locations susceptible to tsunamis. However, not all coastal areas are covered by these maps. In addition, most communities that have experienced tsunamis have historic and geologic records that indicate high-risk areas. Most of this experience has been with distant-source tsunamis, not the rare local source tsunamis. For rare tsunami events, very few coastal communities have any records at all.

The site analysis phase can be used to establish site plan parameters for tsunami mitigation. Many communities have mapped hazard areas. Within these areas, communities may also have more detailed plans that include site analysis. The analysis typically includes geographic conditions, critical infrastructure (see Background Paper #6), area access and egress (see Background Paper #7), and existing and future development patterns. Other considerations include economic feasibility and community design objectives.

Regional hazard maps can identify many of these at-risk areas, but typically they do not reflect the catastrophic potential of a tsunami that is accompanied by other disasters. Besides inundation, near-source earthquakes can cause damage and possibly lower the elevation of the entire region, causing flooding. Fires, broken infrastructure, liquefaction, mudslides, erosion, and other hazardous conditions can create scenarios that make communities even more vulnerable to tsunami waves. Therefore, each site assessment should identify other hazardous conditions besides elevation and shoreline configuration.

Designing for Specific Site Conditions

Communities and project sponsors need to assess the types of shoreline conditions of the site in order to identify a mitigation strategy. The following summarizes various types of shoreline conditions and related site planning considerations.

Beach Communities

Many cottages and homes located along beaches are susceptible to tsunami damage. Numerous tsunami deaths have occurred in these small rural communities. Existing access roads and lot patterns have been developed without considering potential tsunami inundation. Over time these areas have been subdivided and more individual homes added.

In larger resorts, hotels have been located parallel or diagonal to the shore to capture views with recreational facilities in between the shoreline and buildings. Unless designed to withstand a tsunami, these structures are vulnerable.

Beach communities exist because of the lifestyle and visitor industry opportunities created by the water. Therefore, adjacency and views of the beach are at a premium. Many beach communities have to balance their economic dependence on the ocean setting and their tsunami risk.

There are also large regional-serving facilities located in low-lying shoreline areas. Older sewage treatment facilities, power plants, and industrial uses may be located within inundation areas. Inundation of these facilities can cause severe environmental damage from chemicals and bacteria.

Bays

Bays, coves, and river inlets are especially susceptible to tsunami run-up. Their morphology can funnel water into rural delta and valley communities, inundate harbors and town centers, and knock out bridges. Tsunami damage can increase in a scenario that includes high tides, storm surge, or liquefaction from an earthquake.

Harbors

"Tsunami" means "harbor wave" in Japanese. Harbor towns provide the best-known case studies of tsunami disasters. They are susceptible for many of the reasons mentioned previously. They are in coves, may have rivers, and are developed close to the water's edge. Small shipyards, fishing fleets, marinas, and commercial activities ring harbors. One of the things most notable about tsunami aftermath mapping of harbor towns is where all the boats end up.

Ports

In the past 30 years, commercial maritime facilities have shifted to containerization, which requires large paved yards. These slick surfaces can spread wave damage and float trailer-sized debris.

MITIGATION STRATEGIES

Many communities work with project sponsors to select a mitigation approach during the site planning process. Generally, this includes siting solutions that avoid, slow, steer or block inundation. These can be blended with building design and engineering that provides hardened or passive ways of handling the force of a tsunami (see Background Paper #5). Depending on the land uses and site characteristics, a single or hybrid mitigation approach could be used.

There are four basic site planning techniques that can be applied to projects to reduce tsunami risk:

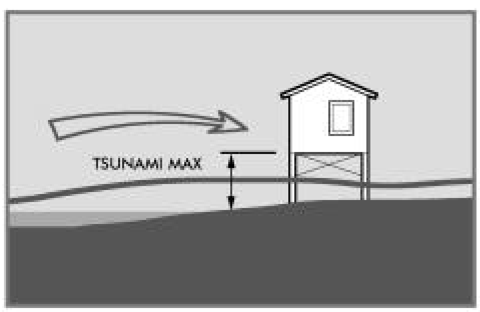
- Avoid inundation areas;
- Slow water currents;
- Steer water forces; and
- Block water forces.

These basic strategies can be used as separate mitigation approaches or be combined into a broader strategy. These include passive methods to allow tsunamis to pass through an area without causing major damage, and methods to harden structures and sites to withstand the force of a tsunami. The efficacy of these techniques depends on the intensity of the tsunami event. If the tsunami hazard is underestimated, development in the area may still be vulnerable to a larger event.

The techniques can be studied both in plan and site sections to reveal vertical stratification of uses, avoidance, and barriers; and in the plan view to understand where water is steered by development, egress routes, and the potential distribution of debris.

Avoiding

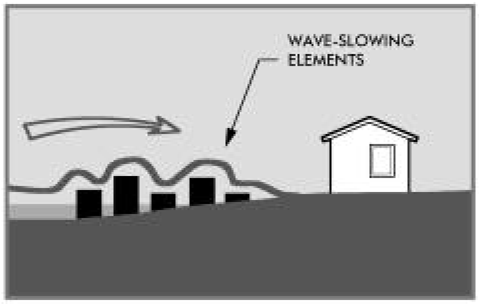
Avoiding a tsunami hazard area is, of course, the most effective mitigation method. At the site planning level, this can include siting buildings and infrastructure on the high side of a lot or elevating structures above tsunami inundation levels on piers or hardened podiums.



Avoiding

Slowing

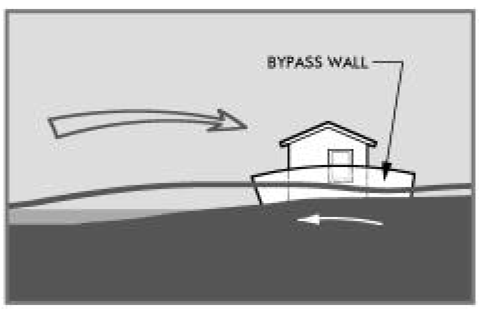
Slowing techniques involve creating friction that reduces the destructive power of waves. Specially designed forests, ditches, slopes, and berms can slow and strain debris from waves. To work effectively, these techniques are dependent on correctly estimating the inundation that could occur.



Slowing

Steering

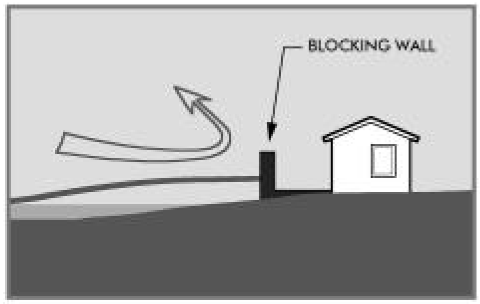
Steering techniques guide the force of tsunamis away from vulnerable structures and people by strategically spacing structures, using angled walls and ditches, and using paved surfaces that create a low-friction path for water to follow.



Steering

Blocking

Hardened structures such as walls, compacted terraces and berms, parking structures, and other rigid construction can block the force of waves. Blocking, however, may result in amplifying wave height in reflection or in redirecting wave energy to other areas.



Blocking

Mitigation Strategies for Various Types of Development

The following describes various types of new development that may be exposed to tsunami damage and identifies possible mitigation strategies for these different types of development.

Infill Housing

In small communities, individual homes and infill housing are the most common development. Often, there is great political pressure to allow development of smaller sites that do not permit locating development out of the hazard area. Communities can require that these smaller projects be raised above inundation levels and that engineering features be added to their design. However, they can still be vulnerable to debris and other structures that may break free and collide with them. In some cases, new infill buildings can be sited on the high side of a lot to avoid being hit by another structure.

New Neighborhoods and Subdivisions

To reduce tsunami damage, the layout of new subdivisions in shoreline areas can include:

- providing maximum spacing between buildings;
- elevating buildings above inundation levels;
- placing houses behind a tsunami control forest or larger hardened buildings; and
- siting primary access roads outside inundation areas and secondary access roads perpendicular to the shore.

High-Rise Hotels

New hotels in coastal areas are typically multi-level concrete frame structures. The lower levels of these buildings can be designed for public areas such as lobbies and support uses (such as parking) for upper level rooms. In Hawaii, for example, lower levels of hotels have been designed to allow waves to pass through the ground floor parking, lobby, and service spaces leaving upper level rooms and meeting spaces undamaged. These buildings must be designed to withstand both tsunami and earthquake forces.

Elevated restaurant in Hilo, Hawaii. Lower level is designed to allow waves to pass through.
Credit: Mintier & Associates

Resorts

Resorts can include a broad range of facilities and services, including small-scale cottages, large hotels, tennis facilities, swimming pools, golf, and beach-related recreation. Resort planning can draw on a variety of mitigation methods, including open space and tsunami forests, elevating or locating structures above estimated inundation levels, and buffering smaller buildings with larger hotels and waterfront structures.

Community Commercial

The downtowns of most coastal communities are located adjacent to piers and beach areas. The primary access roads typically follow the coastline and are lined with commercial enterprises. Both of these development patterns are susceptible to damage by tsunamis. Strengthening and expanding harbor structures can help protect adjacent commercial areas. Depending on the tsunami, however, breakwaters can be swamped by the rising tide and be ineffective. New buildings can be elevated above inundation levels and hardened and designed to withstand tsunami forces.

Industrial

Dry docks, refineries, power plants, and other shoreline industrial facilities are of special concern. In large tsunamis, damaged oil facilities and shoreline industry can wreak havoc in harbors and bays. Destruction or flooding of industrial facilities can add another environmental dimension to a tsunami disaster with burning oil, toxic chemicals, and other hazardous materials. Floating buildings, debris, and boats can crush pipes and tanks. Protecting industrial facilities with walls and stronger anchoring can help; however, locating these types of uses outside inundation zones is the most effective mitigation technique.

Damage to port facilities in Seward, Alaska, from the 1964 tsunami.
Locating industrial facilities outside inundation zones is the most effective mitigation technique.
Credit: U.S. Army Corps of Engineers

Essential and Critical Facilities

Fire stations, power substations, hospitals, sewage treatment facilities, and other critical infrastructure generally should not be located in inundation zones. Relocation of these types of facilities out of inundation areas should be an integral part of any tsunami mitigation plan. Where essential service facilities such as fire stations or permanent lifeguard stations must be located in tsunami hazard areas, they should be designed or retrofitted to survive tsunami damage. This topic is discussed in more detail in Background Paper #6.

Table 4-1 identifies possible mitigation methods for these different types of development.

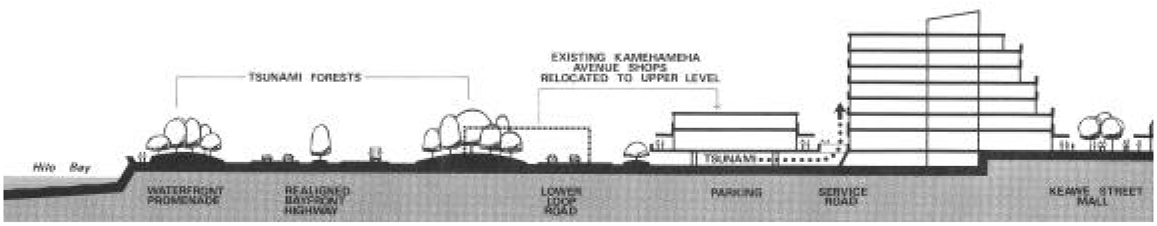
Table 4-1. Mitigation Methods for Selected Types of Development

	Avoidance Methods	Steering Methods	Slowing Methods	Blocking Methods
Infill Housing	• Locate on high side of lot • Elevate above inundation levels on piles or fill	• Maximum spacing between buildings	• Plant tsunami forest in front of single family neighborhoods	• Place larger structures in front of single family structures
New Neighborhoods and Subdivisions	• Locate on high side of lot • Elevate above inundation levels on piles or fill • Locate access roads outside inundation areas	• Maximum spacing between buildings • Place buildings to steer water and floating debris and structures away • Walls and ditches	• Plant tsunami forest in front of single family neighborhoods • Walls and ditches	• Place larger structures in front of single family structures
High-rise Hotels	• Locate rooms above inundation levels on a parking podium • Orient narrow face of the building towards tsunami	• Place buildings to steer water and floating debris and structures away • Walls and ditches	• Place buildings to slow water and floating debris • Walls and ditches • Plant tsunami forest	• Walls • Hardened building design
Resorts	• Locate smaller buildings on the high portions of the site • Elevate structures above inundation levels on piles or fill • Orient narrow face of the building towards tsunami • Locate access roads outside inundation areas	• Maximum spacing between buildings • Place buildings to steer water and floating debris and structures away • Walls and ditches • Grade and pave surfaces	• Place buildings to slow water and floating debris • Walls and ditches • Grading • Plant tsunami forest	• Place larger structures in front of smaller structures • Walls • Hardened building design • Breakwaters for marinas
Community Commercial	• Elevate structures above inundation levels on piles or fill • Orient narrow face of the building towards tsunami • Locate access roads outside inundation areas	• Walls and ditches • Grade and pave surfaces	• Place buildings to slow water and floating debris • Walls and ditches • Grading • Plant tsunami forest	• Walls • Hardened building design
Industrial	• Elevate structures above inundation levels on piles or fill • Locate hazardous and critical operations on high side of lot or relocate • Orient narrow face of the building towards tsunami • Locate access roads outside inundation areas	• Place buildings to steer water and floating debris and structures away • Walls and ditches • Grade and pave surfaces	• Place buildings to slow water and floating debris • Walls and ditches • Grading • Plant tsunami forest	• Place larger structures in front of smaller structures • Walls • Hardened building design • Breakwaters for docks
Critical Facilities	• Relocate facilities to areas outside inundation zone	NA	NA	NA

CASE STUDY: HILO DOWNTOWN DEVELOPMENT PLAN

The Hilo Downtown Development Plan was adopted in 1974 to guide efforts to revitalize the downtown core of Hilo, Hawaii. The Plan established a Safety District based on the 1946 and 1960 inundation experience lines. All redevelopment in the Safety District was subject to urban design and building design standards. Any structure below the 20-foot elevation contour line was required to be designed to withstand the force of a major tsunami. A Parking District was also designated in the Plan to provide parking for downtown businesses and to use parking structures as a protective barrier for inland structures from a tsunami. Parking facilities have been constructed in accordance with the Plan.

In 1985, the Hilo Downtown Development Plan was superceded by the Downtown Hilo Redevelopment Plan under the authority of Chapter 27, Flood Control, of the Hawaii County Code.



A section through the lower downtown area from the *Hilo Downtown Development Plan. Credit: County of Hawaii*

BACKGROUND PAPER #5: BUILDING DESIGN

INTRODUCTION

This paper describes how tsunami risk can be mitigated through building design and construction. It describes considerations that affect the design and construction of buildings in tsunami hazard areas, describes available building codes and guidelines relating to tsunami-generated forces, and provides general advice on an approach to the design of new and the retrofit of existing buildings. Companion Background Paper #3 focuses on avoiding tsunami hazard areas through land use planning, and Background Paper #4 addresses reducing tsunami damage through site planning.

Damage to buildings in Hilo, Hawaii, from the 1946 tsunami.
Credit: Pacific Tsunami Museum

KEY CONCEPTS AND FINDINGS

This background paper presents five key concepts. Essentially, these are an extension of those presented in Background Papers #3 and #4, which deal with planning decisions and site considerations. Assuming planning and zoning requirements are met and that the site is or can be made usable, the design and construction process can begin. The best time to consider preventing tsunami losses to buildings is during the earliest project design stage where the performance objectives and standards are set. These decisions govern the final design and eventual construction.

Concept 1: Understand and Describe the Nature and Extent of Tsunami and Other Hazards Affecting the Building Site

Background Paper #1 provides background information needed to conduct local tsunami risk studies, and Background Papers #3 and #4 focus on planning and siting considerations. While general "rules" exist to prevent losses to buildings, they have to be applied on a building-by-building basis because of differences in uses, sizes, configurations, materials, site characteristics, and other factors. Mitigation considerations include:

- Working in advance with the project's sponsors/owners to ensure an understanding of the risk and general strategies for preventing future losses;
- Adapting and applying appropriate codes and standards to the building design;
- Ensuring site characteristics and mitigation measures are considered in the design; and
- Enforcing design and construction requirements through adequate and independent plan checking and construction inspection procedures.

Concept 2: Determine the Performance Objective for the Building or Structure and the Uses it Will Provide

For many reasons, some buildings are more important than others. This may be due to their function, nature of their occupancy, or activities included in them. For example, hospitals and schools may be assigned higher performance objectives than those given to tourist accommodations. Regardless, every building in a tsunami-hazard area should be constructed to at least meet the minimum tsunami-resistant building code requirements. Several activities include:

- Ensuring the community has adequately enforced minimum code requirements appropriate for the tsunami hazard and for other local hazards;
- Determining which buildings, because of their higher relative importance, should be governed by higher-than-minimum codes, standards, and approval and inspection processes; and
- Requiring through the plan review and construction inspection processes that the importance of the building is recognized and adhered to in construction.

Concept 3: Avoid Constructing New Buildings in High Tsunami Hazard Areas

Insofar as practical, siting new buildings in high hazard areas should be avoided. This reduces community vulnerability by limiting exposure in high hazard areas. Key strategies include:

- Examining proposals and plans for new buildings to see if equally efficient alternative locations can be used;
- Determining if incentives, such as transferring development rights, are available and can be used to promote development in less hazardous areas; and
- Enacting controls to prevent the construction of new buildings—and possibly requiring the removal of many existing ones—in the high hazard areas.

Concept 4: Require Buildings to be Elevated Above the Expected High Water Elevation

As in other flood hazard management programs, buildings can be required to be elevated above the expected tsunami inundation level. This would mean having open ground floors with restricted uses. Key considerations could include:

- Requiring similar elevated design requirements of buildings in tsunami areas as are required in flood prone locations;

- Ensuring that design standards exist that account for tsunami forces and earthquake ground motions; and

- That construction requirements account for water borne debris impact in addition to the tsunami force itself.

Concept 5: Use Qualified Coastal and Structural Engineers and Architects Experienced in Designing (or Retrofitting) Buildings to Resist Tsunami Forces and the Effects of Inundation

Good design and engineering can greatly minimize the effects of tsunamis on buildings. Communities should ensure that design professionals qualified in structural, coastal, and geotechnical engineering are used on projects in high hazard areas. Communities should:

- Identify proposed projects that should involve specially qualified professionals;

- Ensure that project sponsors secure the specialized assistance as early as possible in their project planning; and

- Locate both local and distant sources of qualified assistance that can be contacted when needed.

OVERVIEW OF EXISTING REGULATIONS AND PROGRAMS

Although good engineering techniques and materials will help a building resist tsunami forces and inundation, in cases of intense tsunamis, they only will reduce losses but not prevent severe damage. The best approach to minimizing or avoiding tsunami losses is to locate buildings beyond the reach of run-up.

The design of a building to achieve a particular performance level following tsunamis—that is, the amount of damage the owner can tolerate and the ability of the building to support its intended uses after tsunamis strike—depends on an integrated set of decisions that begin with determining the importance of the building, understanding the consequences of damage, and deciding how much damage can be tolerated. A performance objective expresses this tolerance. Performance depends on the intensity of the tsunami hazard; the location of the building and its configuration (size, shape, elevations, orientation); building codes and standards; choice of structural and finish materials; reliability of utilities; the professional abilities of designers; and the quality of construction. Building codes and standards are but one aspect of an integrated set of planning and design decisions that affect the construction cost, day-to-day functionality, the value of facilities, and their susceptibility to damage. Achieving the desired performance requires that all who participate in decisions affecting these factors agree on performance expectations, understand how their decisions affect performance, and are able to do the work. Ultimately, the owner is responsible for defining acceptable performance and for ensuring the entire design and construction team follows through.

Damage to building in Hilo, Hawaii, from the 1960 tsunami.
Although there are engineering techniques and materials that can be used to resist tsunami forces and inundation, in cases of intense tsunamis, they will only reduce losses but not prevent severe damage.
Credit: Pacific Tsunami Museum

Building design is governed by engineering principles and practices and building codes that establish minimum standards relating to public health and safety. However, codes are not a substitute for competent engineering and design or construction and quality assurance. The circumstances applicable to each building differ, and thorough and independent consideration must be given to each building to be sure the approach and results are appropriate. Each design professional must maintain expertise in this rapidly advancing area of specialization and exercise independent judgement. Knowledge regarding tsunamis and building performance is constantly changing and improvements should be anticipated.

Building Codes

Building construction in the United States is governed at the local level by building codes. Building codes establish minimum acceptable requirements for protecting life, addressing property damage, and preserving the public health, safety, and welfare in the built environment. Building codes are applied to new construction as well as existing buildings undergoing reconstruction, repair, rehabilitation or alteration, or when the nature of the use is changed to a new occupancy that increases the risk or exceeds the structural capability of the building.

Most local building codes used in the Pacific states are modified or unmodified versions of the Uniform Building Code (UBC) prepared by the International Conference of Building Officials. In California, Oregon, and Washington, the state governments mandate code adoption and enforcement at the local level. Alaska only mandates adoption of a fire code and Hawaii does not have a state-mandated building code (see Background Paper #2). However, all the counties in Hawaii and the larger cities in Alaska have adopted a version of the UBC. The three Pacific States mandating the use of the UBC allow local government amendments that are more stringent than the state-mandated code.

The UBC includes design requirements and standards for fire, wind, floods, and earthquakes, but it does not contain requirements for tsunami-resistant design. Appendix Chapter 31, Division I, contains provisions for flood-resistant construction consistent with the requirements of the FEMA Flood Insurance Program. These requirements apply to buildings or structures in flood hazard zones and coastal high hazard zone (V zones). According to these provisions, buildings and structures are to be located at an elevation above the base flood elevation. Portions of the structure below this elevation have use limitations and must either be designed to break away or be impermeable to water. Structural members and impermeable walls are to be designed for flood water forces and scour. Specific rules are not given, but a licensed architect or engineer must be responsible for the design and provide calculations supporting the design to the building official.

The City and County of Honolulu enforces the Uniform Building Code and special requirements for flood and tsunami adopted as Article 11, *Regulations Within Flood Hazard Districts and Developments Adjacent to Drainage Facilities*, as part of its Revised Ordinances. It applies to the design and construction of all new buildings and structures, relocation and major alterations, and additions to or reconstruction of existing buildings lying within the flood hazard and coastal high-hazard districts as delineated on the flood boundary and floodway maps and flood insurance rate maps published by the Federal Emergency Management Agency. Article 11 includes provisions for structural design of buildings and structures subject to coastal flooding specifically addressing hydrostatic loads, hydrodynamic loads, impulsive loads, soil loads, and tsunami loads. The tsunami loads include buoyant forces, surge forces, drag forces, impulse (impact) forces, and hydrostatic forces. Article 11 serves as a general model regarding how a municipality might address tsunami forces through its building code. However, the technical provisions of the ordinance are not recommended because of significant differences in the design forces derived in Article 11 compared to the forces derived by application of the FEMA *Coastal Engineering Manual*. Consensus values, or values based on the latest research, should be used in calculating dynamic and impulsive forces and other factors used in building design. The text of Article 11 is included in Appendix 5-1 and can be found at:

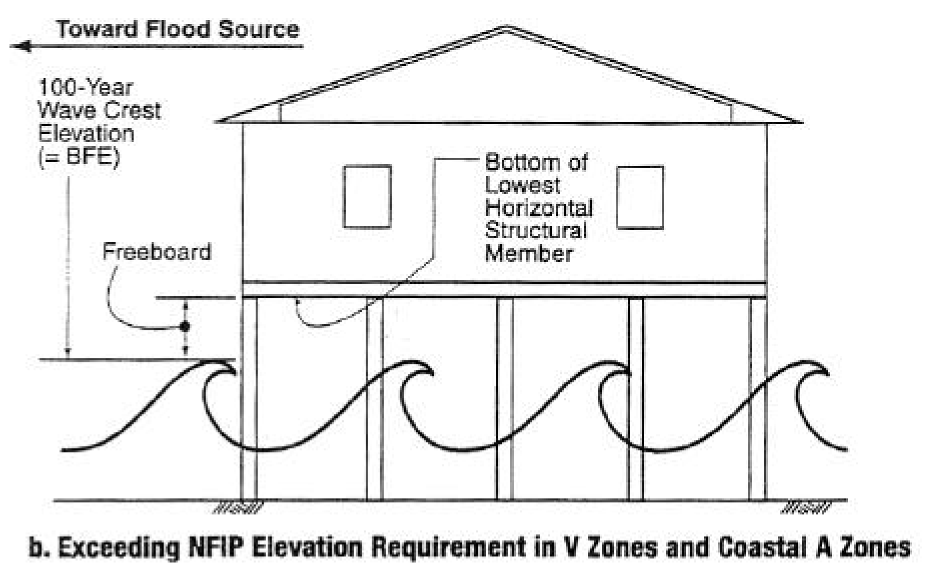
(http://www.co.honolulu.hi.us/refs/roh/16a11.htm).

Relationship to Other Hazards

Tsunamis are only one of several hazards affecting development located along the coastal margins of the states bordering the Pacific Ocean. The key components of resistance to tsunami, earthquake, flood, fire, erosion, and other hazard-induced forces are: competent designs prescribing continuous and well-connected structural systems, and proper construction using quality materials and skilled workers. While force levels and conditions during different types of hazard events vary considerably, there are common factors. Following code requirements for these other hazards will improve tsunami resistance of buildings, especially those located in areas where large hydrodynamic and impact forces are not expected. Because of these common factors, a fundamental measure to improve the performance of buildings in tsunamis is to enforce building codes and standards addressing all of the hazards at a site.

Coastal Engineering Guidelines

Guidance for architects and engineers in the design for tsunami forces is included in the revised version of FEMA's *Coastal Construction Manual,* also known as FEMA 55. The manual deals with tsunamis in a manner similar to the Honolulu ordinance, but there are significant differences. The *Coastal Construction Manual* refers to many newer documents and is more timely than the Honolulu ordinance, which appears to have been amended last in 1987. Appendix 5-2 consists of a comparison of Section 16-11.5 of Article 11 of the City and County of Honolulu code with Chapter 11 of Volume II of the revised FEMA *Coastal Construction Manual*.



Flood Zone V requirements in the *Coastal Construction Manual.*

The Coastal and Hydraulics Laboratory (CHL), a part of the US Army Corps of Engineers Research and Development Center, publishes two relevant documents. The *Shore Protection Manual,* 4th edition, published in 1984, is readily available. However, the manual is undergoing an extensive revision and will be published under a new name, the *Coastal Engineering Manual.* Parts of the new manual are available for review at the CHL web site:

(http://chl.wes.army.mil/library/publications).

A second Corps of Engineers reference, *Coastal Engineering Technical Notes,* is available on the same web site. Technical notes are short descriptions that identify problem areas and provide techniques or data for solutions to engineering problems. The notes promote discussion regarding changing information and are issued as new information becomes available. For example, CETN-III-38 provides a method to compute wave forces on walls. The two manuals and technical notes provide the methods and values needed by engineers to determine force levels and design tsunami-resistant structures.

BUILDING DESIGN PROCESS

The following describes the considerations that should be addressed in the design of new—or the retrofit of existing—buildings in tsunami hazard areas.

Understand the Hazard

The intensity and frequency of tsunami events vary greatly along the Pacific Ocean shoreline and at each locality based on site specific and on-land conditions (see Background Paper #1). Intense tsunami forces associated with wave surge can inundate two- and three-story buildings, create currents in excess of 50 feet per second, propel debris weighing tons, and scour sand from beaches and undermine foundations. In the same event, sites only hundreds of yards away, or nearby sites at higher elevations may only experience the wetting effects of a few feet of slow moving water. Differences in the hazard are critical to design, but they are subject to a great deal of uncertainty. The challenge is defining the hazard in terms relevant to building design.

Define Performance Levels

How a building should perform in a tsunami depends on the uses supported by the building during and after the event and the needs and expectations of the owner and occupants. "Performance levels" describe these expectations in terms of damage and the building's ability to support occupant activities after a hazard event. The desired performance level combined with the probability and intensity of the event, and the level of confidence that the performance will be achieved are combined to express a "performance objective." Although statistically valid quantitative data do not exist to compute structural reliability for tsunami conditions, a qualitative consideration of these factors will give the building owner and design professionals useful information. An owner could consider the following goals:

- Protect the public from harm
- Protect public health (releases of contaminates and toxic and flammable materials)
- Provide essential public emergency services (police, fire, and emergency management)
- Provide the infrastructure needed for commerce (access, utilities)
- Prevent environmental degradation (release of pollutants)

Four performance levels are suggested:

> *Minimum Level*—Buildings located, designed, and constructed to this level can withstand hydrostatic and hydrodynamic forces without being moved off their foundation or off site. Buildings might suffer extensive damage from flooding and may not resist the impact of debris, wave break forces, scour, or ground failure. These buildings would meet the minimum standards for other hazards. Occupants of these buildings must be prepared to evacuate off site to be safe.

Safety Level—Buildings located, designed, and constructed to this level should withstand forces from hydrostatic and hydrodynamic (pushing and drag) pressures and debris and wave-break impact (see Table 5-2 below). They should have foundations designed in anticipation of scour erosion and saturation. People can evacuate vertically to floors above the level of wave action. Extensive damage could be expected to parts of the building affected by flooding and hydrodynamic and debris impact forces, but structural integrity would be maintained. These buildings would be designed to withstand earthquake shaking, induced ground failure, and fire without significant structural damage. Depending on a building's height and location, it could serve as a refuge from near source tsunamis.

Reoccupancy Level—Buildings located, designed, and constructed to this level can withstand the same forces as safety level buildings and be occupied and functional within a few weeks after clean up, minor repairs, and restoration of utilities. Meeting this standard would require more stringent location restrictions and choice of flood-resistant materials. Building location and the elevation of the lower floors are critical considerations.

Operational Level—Buildings located, designed, and constructed to this level can withstand the same forces and effects as in the Reoccupancy Level, but must have back-up emergency systems (utilities, etc.) needed to support use of the building immediately after the tsunami. These buildings preferably would be located outside of the tsunami hazard area.

Select the Intensity of Design Events

Small tsunamis are less damaging, but are more frequent than more intense events. Very large events may be extremely rare and might not be considered except for critical facilities. The probability of occurrence—or the return interval—describes the frequency and intensity of events. Guidance on selecting event frequency and intensity can be taken from the way other hazards are addressed. Design should consider a tsunami with a recurrence of once every 500 years. Buildings with essential uses and large numbers of hard-to-evacuate-people in areas threatened by near-shore-generated tsunamis should consider larger events that recur once every 2,500 years. By designing for a larger event with a longer recurrence interval, the design will consider higher water levels and greater forces. Table 5-1 provides exceedance levels—that is the chance a level will be met or exceeded within a selected time span for different hazards.

Table 5-1. Event Frequency and Design

Hazard Event	Being Exceeded	Return Interval (years)	Design Application
Earthquake			
Design Basis Earthquake (DBE)	10 percent in 50 years	475	Used to determine the design shaking levels for construction under the Uniform Building Code.
Upper Bound Earthquake (UBE)	10 percent in 100 years		Used for design of hospitals, schools, and essential facilities in California.
Maximum Considered Earthquake (MCE) [1]	2 percent in 50 years	2,500 +/-	
Maximum Credible Earthquake			
Flood			
Base Flood	1 percent in one year	100	Defines the Base Flood as the elevation of the crest of the flood. New buildings and substantial improvements to existing buildings must be elevated or "flood-proofed," and manufactured homes raised above this elevation. In Coastal High Hazard Areas[2], the building can be elevated only on a foundation of piers, piles, or columns.
Zone B		500	An area of moderate flood hazard depicted on Flood Insurance Rate Maps as the area lying between the limits of the base and 500-year flood elevations.
Wind			
Normal buildings	2 percent in one year	50	The basic wind speed for buildings if it exceeds the minimum velocity of 70 mph.
Important buildings	~1 percent in one year	~100	An importance factor of 1.15 is used to increase the force from the basic wind speed.

[1] In California where large earthquakes are frequent, the MCE for coastal areas generally has a return period of once per thousand years.

[2] Coastal high hazard flood areas are subject to high velocity water and waves of greater than three feet in height. These areas include hurricane wave wash and tsunamis and are mapped as Zone V. Areas without high velocity are mapped as Zone A. In Zone V areas, all new buildings must be elevated on pilings and columns so: 1) The lowest horizontal structural member is elevated above the base flood level; 2) An engineer or architect certifies the foundation anchoring; and 3) Areas below elevated buildings are open or enclosed using breakaway walls.

Modify Building Codes and Design Standards

Codes, standards, and other requirements currently governing coastal construction should be modified to address tsunami hazards for new buildings and structures. Local jurisdictions should require a minimum performance objective, and encourage owners to decide on higher performance objective(s) if needed. Building code requirements should be enforced for all hazards, especially for earthquakes in areas where local tsunamis may originate. Codes and standards alone do not guarantee buildings capable of withstanding tsunami forces. Engineering judgment, site specific analysis, and good construction are all essential to meeting desired performance objectives. Experienced coastal and structural engineers should be engaged to design important buildings located within tsunami hazard zones. Moreover, all substantial developments should be designed based on a tsunami hazard study completed by a qualified coastal expert.

Recommendations should be coordinated with practices for other hazards, since they share the same principles of resistance and performance (e.g., in Hawaii, tsunami requirements are tied to flood zones determined by FEMA to be coastal flooding zones). In areas where locally-generated earthquakes will cause groundshaking and failure, building code provisions for earthquakes must be enforced.

Anchor bolts. Measures to resist earthquake shaking, such as anchoring and bracing buildings, can also help to reduce tsunami damages.
Credit: Northridge Collection, Earthquake Engineering Research Center, University of California, Berkeley

Adopt and Enforce Special Provisions Governing Removal, Relocation, or Retrofit of Existing Buildings

Retrofit of existing buildings should be encouraged when the effort will improve tsunami resistance to a level capable of meeting identified performance objectives of owners and occupants, or minimize floating debris that can damage nearby buildings. However, relocating buildings to less hazardous locations and considering certain buildings to be expendable are techniques to manage tsunami risk.

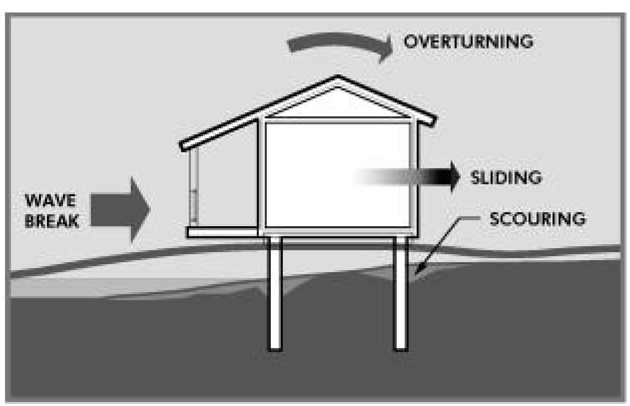
The standards for upgrading buildings involve the same factors as constructing new buildings, but upgrading to achieve a selected performance objective is more expensive to implement after initial construction is completed. Dealing with the vulnerability of existing buildings is difficult because of the limited number of alternatives and cost of remedial activities that will withstand hydrodynamic and impact loads.

Astoria, Oregon, at the mouth of the Columbia River.
Many of the tsunami risk mitigation techniques used for new development can be applied to existing development, but their application will be limited by site constraints and building conditions.
Credit: Army Corps of Engineers

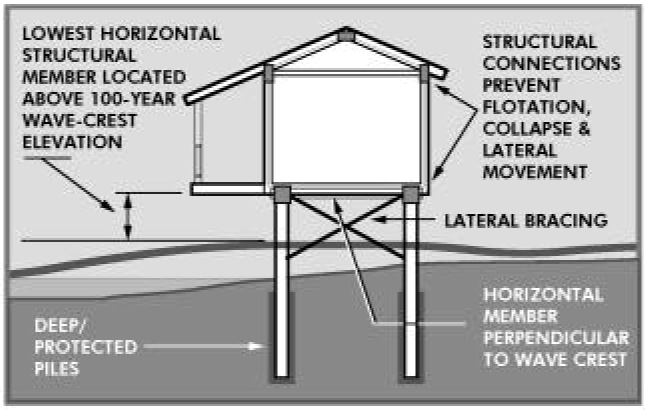
An owner should, in determining the desired performance level, consider the frequency and intensity of the tsunami hazard, the desired level of reliability, and the vulnerability of the building. If the expected performance is unacceptable, various remedial alternatives to improve the performance of the building can be considered. Measures that improve resistance to tsunamis in combination with other more-frequently occurring hazards are more likely to be feasible. These include raising buildings above the base flood elevation, improving foundations to resist scour and erosion, and anchoring and bracing the buildings to resist earthquake shaking. Although these measures will reduce tsunami damages, especially in the statistically-more-frequent small tsunamis, they will not ensure that a building will withstand the intense conditions associated with larger events.

BUILDING CONSTRUCTION MEASURES

Design and construction of new buildings and the retrofitting of existing buildings should address forces associated with water pressure, buoyancy, currents and waves, debris impact, scour, and fire.



Forces on structures created by tsunamis



Design solutions to tsunami effects

Substantially-built buildings of concrete, masonry, and heavy steel frames are likely to do fairly well in a tsunami unless compromised by earthquake shaking. Woodframe buildings, manufactured housing, and light steel frame structures at lower elevations close to the shoreline are likely to fare poorly. However, not every area affected by tsunami run-up will experience damaging forces. Buildings in these less hazardous areas affected by shallow run-up water depths should survive with repairable damage if well designed and constructed. The force of currents and breaking waves, fast-moving waterborne debris, and scouring currents will exceed the resisting capabilities of most buildings unless the building is built with specific design elements and materials.

Table 5-2 describes tsunami effects and possible design solutions.

Table 5-2. Tsunami Effects and Design Solutions

Phenomenon	Effect	Design Solution
Inundation	• Flooded basements • Flooding of lower floors • Fouling of mechanical, electrical, and communication systems and equipment • Damage to building materials, furnishings, and contents (supplies, inventories, personal property) • Contamination of affected area with waterborne pollutants	• Choose sites at higher elevations • Raise the building above the flood elevation • Do not store or install vital material and equipment on floors or basements lying below tsunami inundation levels • Protect hazardous material storage facilities that must remain in tsunami hazard areas • Locate mechanical systems and equipment at higher locations in the building • Use concrete and steel for portions of the building subject to inundation • Evaluate bearing capacity of soil in a saturated condition
	• Hydrostatic forces (pressure on walls caused by variations in water depth on opposite sides)	• Elevate buildings above flood level • Anchor buildings to foundations • Provide adequate openings to allow water to reach equal heights inside and outside of buildings • Design for static water pressure on walls
	• Buoyancy (flotation or uplift forces caused by buoyancy)	• Elevate buildings • Anchor buildings to foundations
	• Saturation of soil causing slope instability and/or loss of bearing capacity	• Evaluate bearing capacity and shear strength of soils that support building foundations and embankment slopes under conditions of saturation • Avoid slopes or provide setback from slopes that may be destabilized when inundated
Currents	• Hydrodynamic forces (pushing forces caused by the leading edge of the wave on the building and the drag caused by flow around the building and overturning forces that result)	• Elevate buildings • Design for dynamic water forces on walls and building elements • Anchor building to foundations
	• Debris impact	• Elevate buildings • Design for impact loads
	• Scour	• Use deep piles or piers • Protect against scour around foundations
Wave break and bore	• Hydrodynamic forces	• Design for breaking wave forces
	• Debris impact	• Elevate buildings • Design for impact loads
	• Scour	• Design for scour and erosion of the soil around foundations and piles
Drawdown	• Embankment instability	• Design waterfront walls and bulkheads to resist saturated soils without water in front • Provide adequate drainage
	• Scour	• Design for scour and erosion of the soil around foundations and piles
Fire	• Waterborne flammable materials and ignition sources in buildings	• Use fire-resistant materials • Locate flammable material storage outside of high-hazard areas

APPENDIX 5-1: CITY AND COUNTY OF HONOLULU, ARTICLE 11. REGULATIONS WITHIN FLOOD HAZARD DISTRICTS AND DEVELOPMENTS ADJACENT TO DRAINAGE FACILITIES

Revised Ordinances of the City and County of Honolulu 1990[1, 2]

Article 11. Regulations Within Flood Hazard Districts and Developments Adjacent to Drainage Facilities

Sections:

Sec. 16-11.1 Applicability.

(a) General. The provisions contained herein are applicable to the construction of all new buildings and structures, relocation and major alterations, additions or reconstruction of existing buildings within the flood hazard districts as delineated on the flood boundary and floodway maps and flood insurance rate maps, and any amendments by the Federal Emergency Management Agency, on file with the department of land utilization, City and County of Honolulu.

These provisions shall also apply to developments adjacent to drainage facilities outside the flood hazard district which are determined to be within a floodway area or a flood fringe area in accordance with Section 21-7.10-9.

(b) Nonconforming Buildings. Any building or structure which was previously lawful prior to the effective date of this article but which is not in conformity with this article may be continued subject to the provisions of Section 21-7.10-12.

(c) Exemptions. The provisions contained herein shall not apply:

(1) To buildings and structures exempted from the flood hazard district provisions under Section 7.10-13;

(2) To buildings and structures which have been granted a flood hazard variance under provisions of Section 21-7.10-11.

(Sec 16-7.1, R.O. 1978 (1983 Ed.); Sec. 16-5.1, R.O. 1978 (1987 Supp. to 1983 Ed.); Am. Ord. 90-57)

Sec. 16-11.2 Definitions.

For the purpose of this article, the following terms are defined in Article 9 of Chapter 21:

Coastal high hazard district;
Flood elevation;
Flood fringe;
Flood hazard district;
Floodproof;
Floodway;
Regulatory flood.

(Sec. 16-7.2, R.O. 1978 (1983 Ed.); Sec. 16-5.2, R.O. 1978 (1987 Supp. to 1983 Ed.); Am. Ord. 90-57)

(1) The ordinance uses the letter “p” to represent the density of water although common usage in engineering is the Greek letter “rho”.

(2) The ordinance uses the term “impact force” to describe the force caused by the collision of a body carried by currents with the structure in question. However, the force is more properly an “impulsive force” because it is related to a change in momentum.

Sec. 16-11.3 Floodproofing requirements in certain areas.

(a) General. Building permit applications for structures which are required to be floodproofed under the provisions of Section 21-7.10 and this article shall be accompanied by a statement of a registered professional engineer or architect that to the best of such person's knowledge, information and belief, the floodproofing methods are adequate to resist the flood depths, pressures, velocities, impact and uplift forces, and other factors associated with the flood, including flood waters due to tsunamis in coastal high hazard districts.

(b) Floodproofing of Buildings above Regulatory Flood Elevation. All buildings and structures which are required to be elevated above the regulatory flood elevation shall be floodproofed by building on natural terrain above the regulatory flood elevation on natural undisturbed ground or by building on stilts or by building on fill (unless fill is specifically prohibited by Section 21-7.10, in the particular flood hazard district) or by other approved methods.

(c) Waterproofing of Buildings Below Regulatory Flood Elevation. Any building or portion thereof, not used for human habitation, and which is permitted to be below the regulatory flood elevation shall either have the space below the regulatory flood elevation free of obstructions or shall be designed and constructed so that below the regulatory flood elevation, the structure is watertight with walls substantially impermeable to the passage of water and with structural components having the capability of resisting hydrostatic and hydrodynamic loads and effects of buoyancy due to the regulatory flood. Compliance with the waterproofing provisions of the "Flood-Proofing Regulations," pamphlet No. EP1165 2 314, published for the Office of the Chief Engineers, U.S. Army, Washington, D.C., shall be deemed to be in compliance with this section. Within coastal high hazard districts, however, any usable enclosed space below the regulatory flood elevation shall be constructed with breakaway walls intended to collapse under stress without jeopardizing the structural support of the building. Areas enclosed by such breakaway walls shall not be used for human habitation.

(Sec. 16-7.3, R.O. 1978 (1983 Ed.); Sec. 16-5.3 R.O. 1978 (1987 Supp. to 1983 Ed.); Am. Ord. 90-57)

Sec. 16-11.4 Floodproofing methods.

(a) Natural Terrain. The following shall be applicable to buildings on natural terrain:

(1) Foundation design shall take into consideration the effects of soil saturation on the performance of the foundation.

(2) The effects of floodwaters on slope stability and erosion shall be investigated.

(3) All utility service lines shall be designed and constructed as provided in the plumbing and electrical codes.

(b) Building on Stilts. Where a building is to be constructed so that the lowest floor is to be elevated above the regulatory flood elevation, the building may be supported on columnar type members, such as columns, piers and in certain cases, walls. Clear spacing of support members, measured perpendicular to the general direction of flood flow shall not be less than eight feet apart at the closest point. The stilts shall, as far as practicable, be compact and free from unnecessary appendages which would tend to trap or restrict free passage of debris during a flood. Solid walls or walled-in columns are permissible if oriented with the longest dimension of the member parallel to the flow. Stilts shall be capable of resisting all applied loads as required by this code and all applicable flood-related loads as required herein. Bracing, where used to provide lateral stability, shall be of a type that causes the least obstruction to the flow and the least potential for trapping floating debris. Foundation supports for the stilts may be of any approved type capable of resisting all applied loads, such as spread footings, mats, piles and similar types. In all cases, the effect of submergence of the soil and additional floodwater-related loads shall be recognized. The potential of surface scour around the stilts shall be recognized and protective measures provided, as required.

(c) Building on Fill.

(1) Except in districts where fill is specifically prohibited as structural support for buildings by Section 21-7.10, as amended, buildings may be constructed on fill material.

(2) The fill shall not adversely affect the capacity of the floodway or any tributary or any other drainage facility or system, and shall be performed in accordance with Chapter 14, ROH 1990, as amended.

(Sec. 16-7.4, R.O. 1978 (1983 Ed.); Sec. 16-5.4, R.O. 1978 (1987 Supp. to 1983 Ed.); Am. Ord. 90-57)

Sec. 16-11.5 Structural requirements.

(a) General. All buildings and structures to be constructed under the provisions of this article shall be capable of resisting all loads required under this chapter and, in addition, all loads prescribed in this section.

(b) Stability.

(1) Overturning or Sliding. All buildings and structures to be constructed under the provisions of this article shall be designed and constructed to provide a minimum factor of safety of 1.50 against failure by sliding or overturning when subjected to combined loads as specified in subsection (d) of this section.

(2) Flotation. All buildings and structures to be constructed under the provisions of this article shall be designed and constructed to resist flotation from floodwater at the regulatory flood elevation with a safety factor of 1.33.

(c) Loads. The following loads shall be considered in the design and construction of buildings and structures subject to the provisions of this article:

(1) Hydrostatic loads;

(2) Hydrodynamic loads;

(3) Impact Loads. Assume concentrated load acting horizontally at the regulatory flood elevation or at any point below it, equal to the impact force produced by a 1,000-pound mass traveling at the velocity of the flood water and acting on a one-square-foot surface of the structure;

(4) Soil Loads. Consideration shall be given to loads or pressures resulting from soils against or over the structure. Computation shall be in accordance with accepted engineering practice with proper consideration for effect of water on the soil. Special consideration shall be given in the design of structures when expansive soils are present;

(5) Tsunami. Structural design of buildings and structures subject to tsunamis shall be in accordance with subsection (f) of this section.

(d) Combined Loads. All loads stipulated in this chapter and all flood-related loads specified under subsection (c) of this section shall be applied on the structure and on structural components, alone and in combination, in such manner that the combined effect will result in maximum loads and stresses on the structure and members. Application of these loads shall be as follows:

(1) Dead Loads. Use at full intensity.

(2) Live Loads. Use at reduced intensity as provided in this chapter for design of columns, piers, walls, foundation, trusses, beams and flat slabs. Live loads on floors at or below the regulatory flood elevation and particularly in basement slabs, shall not be used if their omission results in greater loading or stresses on such floors. Similarly, for storage tanks, pools and other similar structures designed to contain and store materials, which may be full or empty when a flood occurs, both conditions shall be investigated in combination with flood-related loads of the containing structure being full or empty.

(3) Wind Load. Use at full intensity as required in this chapter on areas of the building and structure above the regulatory flood elevation.

(4) Earthquake Load. Combined earthquake and flood-related loads need not be considered.

(e) Allowable Soil Pressures. Under flood conditions, the bearing capacity of submerged soils is affected and reduced by the buoyancy effect of the water on the soil. For foundations of buildings and structures covered by this article, the bearing capacity of soils shall be evaluated by a recognized acceptable method. Expansive soils should be investigated with special care. Soils which lose all bearing capacity when saturated, or become "liquefied" shall not be used for supporting foundations.

(f) Coastal Flood Water Design.[a]

(1) Buildings or structures shall be designed to resist the effects of coastal floodwaters due to tsunamis. The regulatory flood elevation due to tsunamis is considered to result from a non-bore condition, except where a bore condition is shown on the flood insurance maps or in the flood study adopted for the county.

(2) Habitable space in building structures must be elevated above the regulatory flood elevation by such means as posts, piles, piers or shear walls parallel to the expected direction of flow of the tsunami wave. The forces and effects of floodwaters on the structure shall be fully considered in the design.

(3) Allowable stresses (or load factors in the case of ultimate strength or limit design) for the building materials used shall be the same as the building code provides for wind or earthquake loads combined with gravity loads, i.e., treat loads and stresses due to tsunamis in the same fashion as for earthquake loadings.

(4) The main building structure shall be adequately anchored and connected to the elevating substructure system to resist all lateral, uplift and downward forces. In wood construction, toenailing is not allowed.

(5) Scour of soil from around individual piles and piers shall be provided for in the design in the coastal flood hazard district. Shallow foundation types are not permitted unless the natural supporting soils are protected on all sides against scour by a shore protection structure, preferably a bulkhead. Shallow foundations may be permitted beyond 300 feet from the shoreline, provided they are founded on natural soil and at least two feet below the anticipated depth of scour, and provided not more than three feet of scour is expected at the structure. The table below gives estimated minimum depths of soil scour below existing grade as a percentage of the depth (h) of water at the location.

[a] Reference is made to the January 31, 1980, report by Dames & Moore entitled “Design and Construction Standards for Residential Construction in Tsunami-Prone Areas in Hawaii” prepared for the Federal Emergency Management Agency for a more detailed study and analysis of tsunami wave forces.

Estimated Minimum Scour		
	Distance from Shoreline	
	Up to 300 Feet[1]	Greater than 300[2] Feet
Loose sand	80% h	60% h
Dense sand	50% h	35% h
Soft silt	50% h	25% h
Stiff silt	25% h	15% h
Soft clay	25% h	15% h
Stiff clay	10% h	5% h

1 Values may be reduced by 40% if a substantial dune or berm higher than the regulatory flood elevation protects the building site.
2 Values may be reduced 50% if the entire region is essentially flat.

(6) Forces which must be considered in the design of structures elevated to resist floodwaters include:

(A) Buoyant forces - uplift caused by partial or total submergence of a structure.
(B) Surge forces - caused by the leading edge of a surge of water impinging on a structure.
(C) Drag forces - caused by velocity of flow around an object.
(D) Impact forces - caused by debris such as driftwood, small boats, portions of houses, etc., carried in the flood currents and colliding with a structure.
(E) Hydrostatic forces - caused by an imbalance of pressure due to a differential water depth on opposite sides of a structure or structural member.

(7) Buoyant Force. The buoyant force on a structure or structural member subject to partial or total submergence will act vertically through the center of mass of the displaced volume and is calculated from the following equation:

$$F_B = pgV$$

where $F_B =$ buoyant force acting vertically
$p =$ density of water (2.0 $lb\text{-}s^2/ft^4$ for salt water)
$g =$ gravitational acceleration (32.2 ft/s^2)
$V =$ displaced volume of water (ft^3)

(8) Surge Force. The total force per unit width on a vertical wall subjected to a surge from the leading edge of a tsunami which approaches the structure as a bore or bore-like wave is calculated from the equation below. The resultant force acts at a distance approximately h above the base of the wall. (Note: This equation is applicable for walls with heights equal to or greater than 3h. Walls whose heights are less than 3h require surge forces to be calculated using the appropriate combination of hydrostatic and drag force equations for the given situation.)

$$F_S = 4.5\ pgh^2$$

where F_S = total force per unit width of wall
p = density of water (2.0 lb-s^2/ft^4 for salt water)
g = gravitational acceleration (32.2 ft/s^2)
h = surge height (ft)

(9) Drag Force.

$$F_D = \frac{pC_D A u^2}{2}$$

where F_D = total drag force (lbs) acting in the direction of flow
p = density of water (2.0 lb-s^2/ft^4 for salt water)
C_D = drag coefficient (nondimensional) (1.0 for circular piles, 2.0 for square piles, 1.5 for wall sections)
A = projected area of the body normal to the direction of flow (ft^2)
u = velocity of flow relative to body (ft/s) (estimated as equal in magnitude to depth in feet of water at the structure)

The flow is assumed to be uniform, so the resultant force will act at the centroid of the projected area immersed in the flow.

(10) Impact Force.

$$F_I = m\frac{\Delta U_b}{\Delta t}$$

where F_I = impact force (lb)
m = mass of the water displaced by the body impacting the structure (slugs)
$\frac{\Delta U}{\Delta t}$ = acceleration (deceleration) of the body at (ft/s2)
U_b = velocity of the body (ft/s) (estimated as equal in magnitude to depth in feet of water at the structure)
t = time (s)

This single concentrated load acts horizontally at the regulatory flood elevation or at any point below it and is equal to the impact force produced by a 1000-pound weight of debris traveling at the velocity of the flood water and acting on a one square-foot surface of the structural material where impact is postulated to occur. The impact force is to be applied to the structural material at a most critical or vulnerable location determined by the designer. It is assumed that the velocity of the body goes from U_b to zero over some small finite time interval (t) so the following approximation can be made:

$$F_I = \frac{31U}{\Delta t}$$

For structural material of wood construction, assume t, the time interval over which impact occurs, is one second. For structural material of reinforced concrete construction, use t of 0.1 second and for structural material of steel construction, use t = 0.5 second.

(11) Hydrostatic Force.

$$F_H = \frac{1}{2} pg \left\{ h + \frac{u_p{}^2}{2g} \right\}^2$$

Where F_H = hydrostatic force (lb/ft) on a wall, per unit width of wall
p = density of water (2.0 lb-s^2/ft^4 for salt water)
g = gravitational acceleration (32.2 ft/s^2)
h = water depth (ft)
u_p = component of velocity of flood flow perpendicular to the wall (ft/s) (total velocity, u, estimated as equal in magnitude to depth in feet of water at the structure)

The resultant force will act horizontally at a distance of

$$\frac{1}{3} \left\{ h + \frac{u_p{}^2}{2g} \right\}^2$$

above the base of the wall.

(Sec. 16-7.5, R.O. 1978 (1983 Ed.); Sec. 16-5.5, R.O. 1978 (1987 Supp. to 1983 Ed.); Am. Ord. 90-57)

Sec. 16-11.6 Violations--Penalty.

For violation and penalty provisions of this article, see Article 10 of this chapter. (Added by Ord. 90-57)

APPENDIX 5-2: COMMENTARY BY JAMES RUSSELL REGARDING HONOLULU FLOOD HAZARD ORDINANCE PROVISIONS

The structural requirements in section 16-11.5 of Article 11 of the Honolulu Code are in general agreement with the provisions contained in Chapter 11 of Volume II of the revised *FEMA Coastal Construction Manual*. However, there are some significant technical differences as noted below.

The Honolulu code is apparently based on the Dames and Moore report *Design and Construction Standards for Residential Construction in Tsunami-Prone Areas of Hawaii* (1980). The FEMA manual also references that report, but also refers to many more recent documents including: *Introduction to Fluid Mechanics* (Fox & McDonald 1985), *Criteria for Evaluating Flood-Protection Structures* (Walton, 1989), *Wave Forces on Inclined and Vertical Wall Surfaces (ASCE 1995), US Army Corps of Engineering Shore Protection Manual, Volume II* (USACE 1984), *Minimum Design Loads for Building and other Structures* (ASCE 7-98), ASCE 24-98 and *Engineering Principles and Practices for Retrofitting Flood Prone Residential Buildings*, FEMA 259, (1995).

Provisions for “breakaway walls” in any enclosed usable space below the flood elevation are required in the Honolulu ordinance for Coastal High Hazard Districts, which includes tsunami-prone locations. This provision is consistent with NFIP regulatory requirements for Coastal V Zones; however, the specific provisions of 44CFR 60.3(e)(5) and those of FEMA Technical Bulletin 9, regarding design loading and construction details for breakaway walls, are not included.

The effects of five types of structural loading required by the Honolulu ordinance are the same type of loads considered in the FEMA Coastal Design Manual. These include the following:

- Hydrostatic loads;
- Hydrodynamic loads;
- Impact loads;
- Soil loads; and
- Tsunami loads.

A small difference does exist between the Honolulu code and the 1997 UBC regarding the load factor used when applying strength design methods for tsunami loads. The Honolulu code specifies the same factor as for earthquake loads, which is a factor of 1.0 in the 1997 UBC. In contrast, the 1997 UBC specifies a load factor of 1.3 when applying fluid loads in a strength design analysis. Therefore, the Honolulu code is less restrictive in the application of fluid loads.

The effect of scour of soil from around building foundation piles or piers is required in both the ordinance and the FEMA manual. The values for estimating the depth of scour are reasonably consistent between the two documents with the exception that the Honolulu ordinance has reduced scour depths at distances greater than 300 feet from the shoreline, or when a dune or berm higher than the regulatory flood height protects the building site. The FEMA manual reproduces the Honolulu ordinance table on scour depth without using these reductions. The FEMA manual also provides design guidance on the scour produced in non-tsunami conditions along walls.

Design consideration for five types of tsunami forces are required in the Honolulu ordinance and these are consistent with the types of forces considered in the FEMA manual. The five forces in the ordinance include: 1) Buoyant forces, 2) Surge forces (e.g., breaking wave forces), 3) Drag forces (e.g., hydrodynamic forces), 4) Impact forces, and 5) Hydrostatic forces. However, there are differences in the magnitude of those forces between the two documents, the most significant of which occurs in those forces dependent on water velocity (e.g., drag and impulsive forces).

The equation used to determine surge force in the Honolulu ordinance is predicated on a tsunami bore wave. However, the force is smaller than that determined using equation 11.6 in the FEMA manual for a breaking wave in shallow water, typical of coastal flood and storm events. The forces determined for a breaking wave of a given height in the FEMA manual would be 22 percent greater than the surge force from a bore wave of equal height as determined by the Honolulu ordinance. The FEMA document does not specifically address a tsunami bore type wave.

The equation for determining hydrodynamic drag forces in the Honolulu ordinance contains different letters representing certain components of forces than the formula 11-8 in the FEMA manual, but it does contain all of the same elements as in the FEMA document. However, a <u>major</u> difference occurs in the numerical result of the two equations because of the way the water velocity is determined. In the Honolulu ordinance, velocity in feet per second is estimated to equal the depth of the water at the building. Therefore, for a depth of 3 feet, the velocity is assumed to be 3 feet per second. In the FEMA manual, for a 3-foot depth, a 3 feet per second velocity only results when computing the lower bound velocity from formula 11.2.

Three velocity estimates are given in the FEMA manual, lower bound, upper bound and extreme (tsunami), each of which is dependent on the assumed water depth. At an assumed water depth of 3 feet, the upper bound design velocity in feet per second, determined by formula 11.2 in the FEMA manual, would be approximately 3 times greater (10 fps) and result in forces that are 10-1/2 times greater because the drag force is a function of the velocity squared. At this same 3 foot depth, the tsunami design velocity in the FEMA manual would be 6.5 times greater, and result in forces that are 43 times greater than assumed for this depth by the Honolulu ordinance. Ironically, smaller water depths actually result in larger differences between the water velocity that would be determined in the Honolulu ordinance and those determined using the FEMA upper bound or tsunami velocities. The result is that the method used to determine water velocity has a profound effect on the drag loads to be used in a design.

Impact forces also are dependent on water velocity as determined by both the Honolulu ordinance and FEMA formula 11.9. Once again the letters used to designate the individual components of the equations differ between the two documents but the resulting formulas are the same. For impact loads the velocity term is not squared, therefore the difference in forces is directly proportional to any difference in velocity. However, in the FEMA document, the water velocity for impulsive forces is estimated to be one-half of the upper bound velocity as determined by Formula 11.2. Using a 3 foot high water depth example, and assuming a wood post is being impacted by a 1,000 pound object as the Honolulu code would require, the 3 foot per second velocity results in a 3,000 pound force. In the FEMA document, assuming this same water depth and mass of object, the velocity is 4.9 feet per second and results in a 4,900-pound force, or an increase of nearly 65 percent.

Another variable that must be established when determining impulsive forces is the duration of the impact. The Honolulu ordinance gives specific time intervals for the duration of impulsive forces to wood (1.0 second), reinforced concrete (0.1 second) and steel (0.5 second) members. These are also quoted in the text of the FEMA document. However, the FEMA document also provides a Table 11.3 wherein ranges of impact duration are given for walls and piles (columns) of wood, steel, reinforced concrete and concrete masonry. These duration of impact ranges differ from the single values given in the Honolulu ordinance with steel being shorter (0.2- 0.4 sec), concrete being longer (0.2 – 0.6 sec), and wood being slightly shorter (0.5 –1.0 sec) duration.

In conclusion, there is a substantial difference in the magnitude of drag forces, and significant differences in impulsive forces between the two documents, with the Honolulu code providing less resistance to these types of tsunami generated forces.